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PHOTOVOLTAGE CHARACTERIZATION OF MOS CAPACITORS.(U)
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PHOTOVOLTAGE CHARACTERIZATION OF MOS CAPACITORS

R. L. Streever
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Electronics Technology & Devices Laboratory

August 1977

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US ARMY ELECTRONICS COMMAND FORT MONMOUTH, NEW JERSEY 07703

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Surface photovoltage, capacitance and conductance measurements have been made on various metal-oxide-semiconductor (MOS) capacitors fabricated on p-type Si wafers. Curves of photovoltage plotted against dc sample bias are found to exhibit structure arising from surface state effects which correlates well with that observed in the C-V/G-V curves. In the region near the middle of the Si bandgap the surface state density can be reduced by about an order of magnitude by annealing. An equivalent circuit approach is used to relate the photovoltage to the electrical parameters.

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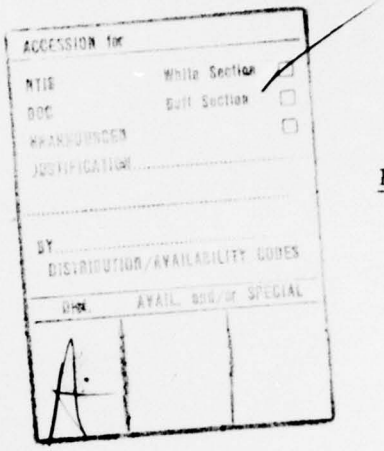

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PHOTOVOLTAGE CHARACTERIZATION OF MOS CAPACITORS

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ABSTRACT

Surface photovoltage, capacitance and conductance measurements have been made on various metal-oxide-semiconductor (MOS) capacitors fabricated on p-type Si wafers. Curves of photovoltage plotted against dc sample bias are found to exhibit structure arising from surface state effects which correlates well with that observed in the C-V/G-V curves. In the region near the middle of the Si bandgap the surface state density can be reduced by about an order of magnitude by annealing. An equivalent circuit approach is used to relate the photovoltage to the electrical parameters.

I Introduction

Studies of the surface photovoltage, which is the change in surface potential accompanying the creation by light of excess carriers in a semiconductor, have been extensively reported in the literature.[1] The possibility of using scanning photovoltage methods to evaluate the interfaces of large scale integrated (LSI) metal-oxide-semiconductor (MOS) devices has created renewed interest in such studies.[2] Preliminary experiments in this direction were made on MOS capacitors to see if one could correlate scanning photovoltages with conventional C-V/G-V measurements.

For evaluation purposes an array of MOS capacitors is usually formed by depositing Al contact dots on oxidized Si wafers either with mechanical masks or by photolithographic techniques. If the Al contacts are made sufficiently thin ($\sim$ 150 A), so that they are essentially transparent to visible light, photovoltage studies can be performed on the individual capacitors. In the present investigation, we have carried out such studies by using as the light source a He-Ne (632.8 nm) laser which could be focused to a spot size of about one micron on the sample surface.

From the point of view of wafer evaluation two types of photovoltage studies are possible. First, one can scan the focused laser beam over a given contact and use the photovoltage variations as a means of detecting microstructure.[2] Second, by chopping the laser beam, one can measure the dc component of the photovoltage at a fixed point on a given contact. Thus, one can try to detect slow systematic variations in the photovoltage at different points on the contact or from contact

to contact. It is this latter approach that was used in the present investigation.

To correlate the photovoltage measurements directly with C-V measurements, we have carried out a theoretical and experimental investigation of the variation of photovoltage with dc bias and its relation to the C-V curves. We show that the photovoltage versus bias (V_p-V) curves can give similar information to that obtained with conventional admittance (G-V/C-V) measurements. The photovoltage measurements have the added advantage that small regions of the surface can be probed for uniformity of properties.

II Theoretical Model

To analyze the dependence of photovoltage on sample bias or surface potential we use an equivalent circuit approach. This has an advantage over more conventional approaches[1] in that it gives expressions for the photovoltage explicitly as a function of frequency and directly in terms of the capacitances and conductances associated with the equivalent circuit of the MOS capacitor.

A simplified equivalent circuit for a p-type MOS capacitor is shown in Fig. 1. This is essentially the same circuit used by Saks[3] to discuss conductance measurements and by Nakhmanson[4] to discuss the photovoltage. Except for the addition of G_o and C_o, the circuit represents a simplification of the equivalent circuit described by Lehovec and Slobodskoy.[5] G_o and C_o represent the recombination conductance and capacitance. G_p and G_n are the surface state conductances for majority and minority carriers, respectively. C_I, C_D and C_s are the inversion layer, depletion layer and surface state capacitance, respectively, while C_{ox} is the insulator capacitance. If the semiconductor is strongly doped so that the carrier concentration ratio n_o/p_o is small (for a p-type material) then to this approximation one can represent the effect of the chopped light source by an ac current source I_L in parallel with G_o.[4]

The circuit of Fig. 1 can be used to give an expression for V_p, the photovoltage developed between the Si surface (point S of Fig. 1) and the bulk substrate. The general expression is rather complex, however, and it is of interest to consider limiting cases.

Case I

No surface states $C_s=G_p=G_n=0$ and C_o small $\omega C_o \ll G_o$. Then V_p is given simply by

$$V_p = -\frac{|I_L|}{G_o}\left(\frac{C_I}{C_I+C_D}\right)\left[1+j\omega\left(\frac{C_I C_D}{C_I+C_D}\right)\frac{1}{G_o}\right]^{-1} \qquad (1)$$

In the low frequency limit the imaginary component of V_p (the component out of phase with respect to I_L) vanishes. The real component will increase from zero as the semiconductor is biased into inversion and will approach a limiting value of I_L/G_o in the strong inversion limit.

Case II

Low frequency limit

In the low frequency limit the following expression for the real component of V_p can be obtained

$$\text{Real } V_p = -\frac{|I_L|}{G_o}\frac{1}{(C_D+C_I+C_s)}\left\{\frac{C_I+C_s\left(\frac{G_n}{G_n+G_p}\right)}{1+\left(\frac{G_n G_p}{G_n+G_p}\right)\frac{1}{G_o}}\right\} \qquad (2)$$

We see that in general there is both a surface state and an inversion layer contribution to V_p.

The surface states also make a contribution to the out-of-phase part of V_p. The expression is rather complex, and since it won't be needed in an experimental analysis we omit it here.

III Experimental

A. Photovoltage System

The photovoltage-bias experiments were carried out using a scanning photovoltage system similar to that described by DiStefano and Viggiano.[6] The system uses a He-Ne 632.8 nm (visible red) laser which is focused on the sample to a spot size of about one micron. When the system is operated in the normal scanning mode, an ac photovoltage signal is induced as the light spot is scanned across a defect. In the present study a light chopper was added to the system so that an ac signal could be developed independently of the scanning. In the typical experiment the light spot was focused near the center of a given contact and a plot of photovoltage versus sample bias was obtained. It was determined that the V_p-V curves were essentially the

same from spot to spot for a given contact so that meaningful comparisons to C-V/G-V measurements, which average over a whole contact, could be made. On a given sample, results for different contacts were also quite similar. The photovoltage was measured by monitoring the ac current through C_{ox} with a sensitive current amplifier. In such a detection scheme the measured current is 90° out of phase with respect to the photovoltage. A lock-in amplifier was used to enable real and imaginary components of V_p to be measured separately.

B. Preliminary Experiments

Preliminary studies were done using MOS capacitors fabricated on <100> orientation p-type Si wafers with resistivities of 2-4 Ω-cm. The wafers was thermally oxidized in dry O_2 at 1000°C to a thickness of 870 Å. An array of transparent Al front contact dots approximately 150 Å thick were deposited by electron beam evaporation through a mechanical mask. Thicker contacts were deposited on the edge of the transparent ones to facilitate electrical connection and an Al back contact was also deposited.

Curves showing the real component of V_p versus sample bias taken at different frequencies of the chopped laser source are shown in Fig. 2. The photovoltage variations about zero bias are due to the presence of surface states and occur in the region around weak inversion.

C. Photolithographic Samples

In order to increase the surface state effects a second set of MOS capacitors were fabricated on <111> orientation p-type Si wafers with resistivities of 1.5 to 2.0 Ω-cm. The dry thermal oxide was about 1,000 Å thick. Transparent Al contacts (approximately 125 Å thick and 2 mm square) were defined by photoresist techniques and deposited by electron beam evaporation. Smaller area thicker contacts (approximately 10,000 Å thick) were also deposited to facilitate electrical connection. One set of samples was left unannealed and one set (from the same wafer) was given a final N_2 anneal at 500°C.

Capacitance and conductance measurements made with a PAR C-V plotter on representative contacts of the annealed and unannealed samples are shown in Figs. 3 and 4, respectively. Photovoltage-bias curves showing the real component of V_p at 200 Hz for the two types of samples are given in Fig. 5.

IV Discussion

A. Capacitance Data

The capacitance curves of Fig. 4 indicate a large distribution

of surface states in the unannealed sample and also a large fixed positive charge distribution which displaces the curves along the voltage axis. Both the surface states and the fixed charge are reduced by annealing, the voltage displacement being about one volt smaller in the annealed sample.

The variation of the surface state capacitance C_S with sample bias can be obtained from the low frequency capacitance data. At low frequencies the C-V curves approach the quasistatic ones and the measured parallel capacitance C_m is given simply by[7]

$$\frac{C_m}{C_{ox}} = \frac{C_D+C_I+C_S}{C_D+C_I+C_S+C_{ox}} \tag{3}$$

Letting C_T be the low frequency capacitance that would be measured in the absence of surface states (i.e., the value of C_m when $C_S=0$), we then have

$$\frac{C_S}{C_{ox}} = \frac{(C_m/C_T-1)}{(1-C_m/C_{ox})(C_{ox}/C_T-1)} \tag{4}$$

In accumulation and depletion where $C_I=0$, the high frequency capacitance curves coincide with the low frequency ones when $C_S=0$. Consequently, in this range C_T can be obtained from the high frequency capacitance curves. In inversion C_T can be obtained from standard calculated C-V curves.

Values of C_S/C_{OX} calculated from Eq. (4) are shown in Fig. 6 for annealed and unannealed samples. In the unannealed sample C_S is seen to peak right around midgap (about -3 volts for this sample) where the slower surface states are most effective. By contrast the annealed sample shows surface state peaks to either side of midgap (about -2 volts for this sample). This is consistent with the shoulders observed in the C-V curves for the annealed sample. The shoulders on the inversion side of midgap tend to be obscured by the inversion capacitance.

The surface states may be due to the electron beam irradiation to which the samples were subjected during evaporation of the contacts. In the photoresist process the Al layer for the thick contacts was deposited over the whole surface and then selectively etched away. Consequently, the whole surface received a large irradiation. The large density of surface states near midgap in irradiated samples would be consistent with the findings of Ma.[8]

B. Conductance Data

From the conductance data of Figs. 3 and 4 we see that conductance peaks occur in both depletion and inversion suggesting that we must consider both majority and minority carrier response. As has been discussed by Saks,[3] surface state conduction can occur in two separate channels. For a p-type device these can be the majority carrier path through G_p or the minority carrier path through G_n and G_o (refer to Fig. 1). If G_o is much greater than G_p and G_n at midgap then both minority as well as majority carrier response has to be considered on a nearly equal basis.

The part of the measured parallel conductance due to surface states can be written[9]

$$\frac{G_m}{\omega} = \frac{C_s \omega \tau C_{ox}^2}{(C_{ox}+C_D+C_s)^2 + \omega^2 \tau^2 (C_{ox}+C_D)^2} \tag{5}$$

Here τ is the surface state time constant. For a given frequency this expression peaks at two values of surface potential. One in depletion when $\omega\tau_p=(C_{ox}+C_D+C_s)/(C_{ox}+C_D)$ and one in inversion when τ_n replaces τ_p. At high frequencies the peaks occur where τ is small (near the bandgap edges). At lower frequencies the peaks come together and merge near midgap where τ_p and τ_n become comparable. This is just the behavior observed experimentally.

Values of C_s obtained using Eq. (5) were found to agree well with those obtained from C-V data and are shown in Fig. 6.

C. Photovoltage Data

We turn now to an analysis of the photovoltage data taken at 200 Hz. In the annealed sample we see a surface state shoulder at about -2.7 volts and a peak at about -1 volt occurring respectively in depletion and inversion (as noted previously midgap in this sample occurs at about -2 volts). These peaks correlate well with surface state peaks in the conductance data and with those observed in the C_s plot. The unannealed sample shows a broad surface state response from about -1.0 volt to about -6 volts which also agrees well with the low frequency conductance peak or with the peak in the C_s plot at about -3 volts (around midgap).

Although the photovoltage correlates well with C_s, there does appear to be a discrepancy with the theory of Section II. According to Eq. (2) the surface state photovoltage should be small in depletion when $G_n/(G_n+G_p) \ll 1$. According to the experimental result, however, surface state response occurs in both depletion and inversion (on both

sides of midgap). It seems likely therefore that the equivalent circuit of Fig. 1 (which in the original Lehovec-Slobodskoy[5] version assumed a negligible recombination rate in the space charge layer) is not the correct one to use.

For the case of infinite recombination rate in the space charge layer Lehovec and Slobodskoy[5] describe a different circuit which puts G_p and G_n in parallel. Such a circuit would give surface state response in both depletion as well as in inversion. Provided C_s was symmetric about midgap, the surface state photovoltage would be symmetric also. It seems that such a circuit could explain, therefore, the photovoltage as well as the conductance data and such a model will be discussed more fully in a future paper.

V. Conclusion

The surface state distribution has been evaluated for p-type MOS samples using admittance and photovoltage techniques and the results correlate well with each other. As might be expected, we find the surface state distribution to vary markedly with annealing. At midgap the surface states are about an order of magnitude smaller in the annealed sample.

These studies should be helpful in the analysis of scanning photovoltage displays. They also point to the possibility of using scanning photovoltage methods for quantitative diagnostic studies of LSI structures.

Acknowledgement

The authors gratefully acknowledge T.H. DiStefano for some initial discussions concerning the development of the scanning photovoltage system and the efforts of E. Ahlstrom, E. Kostyk, N. Korolkoff and J. Finnegan in preparing samples for us.

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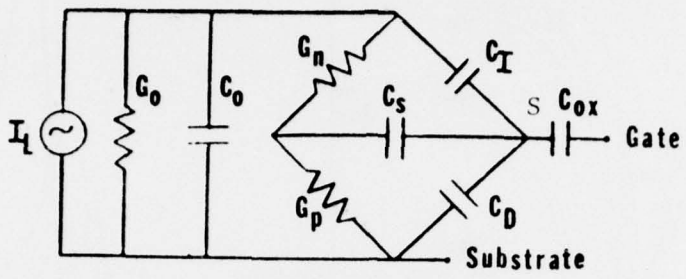

Fig. 1. Equivalent circuit of a p-type MOS device.

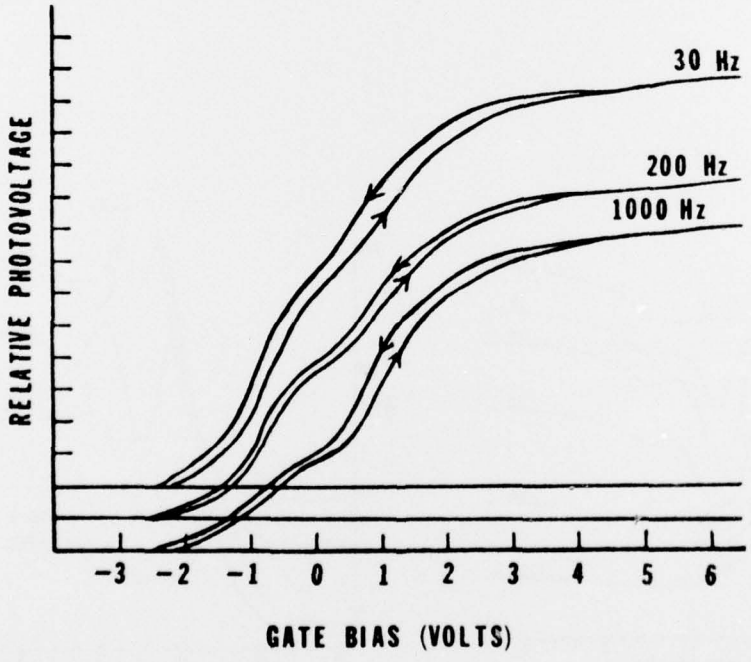

Fig. 2. Real component of photovoltage at different frequencies.

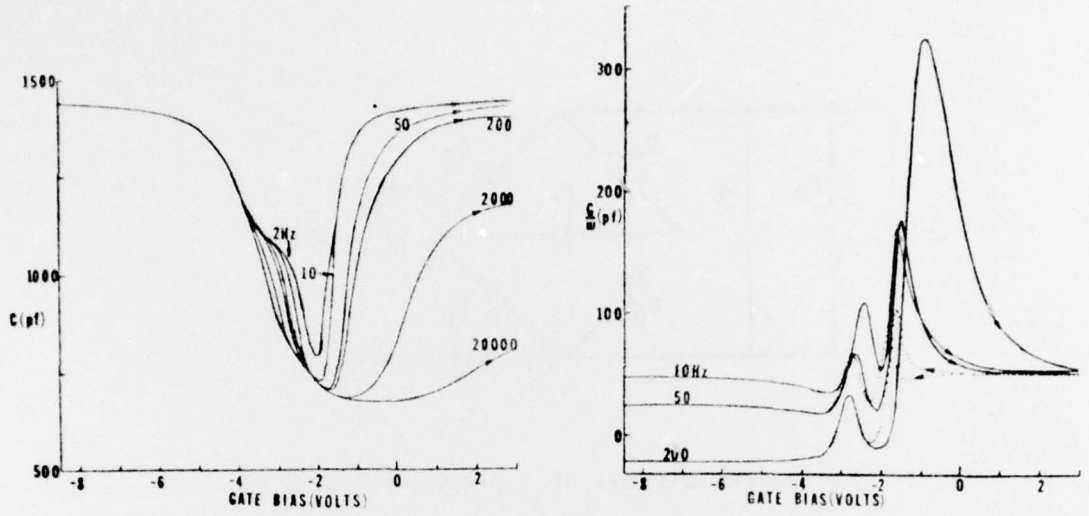

Fig. 3. C-V and G-V curves for annealed sample.

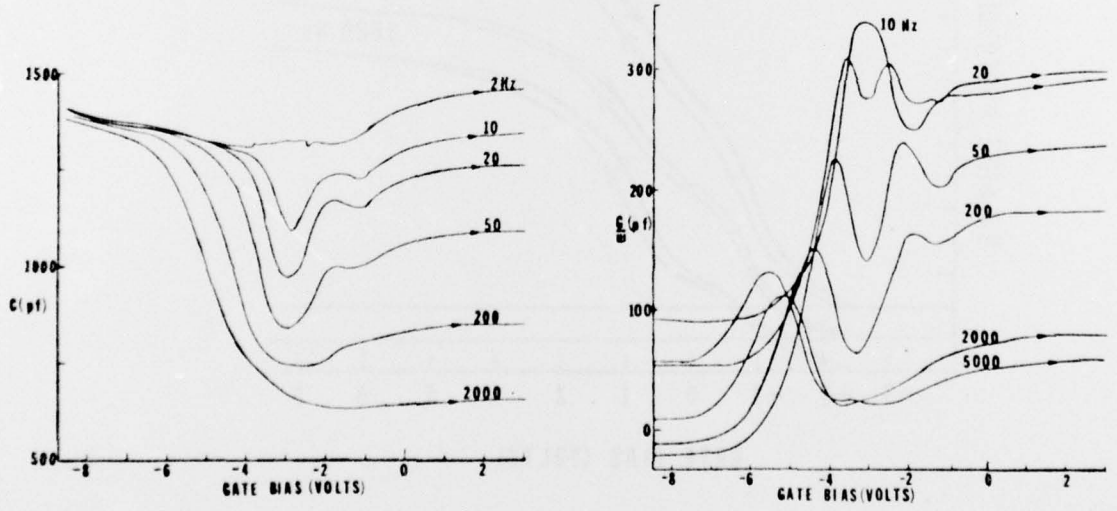

Fig. 4. C-V and G-V curves for unannealed sample.

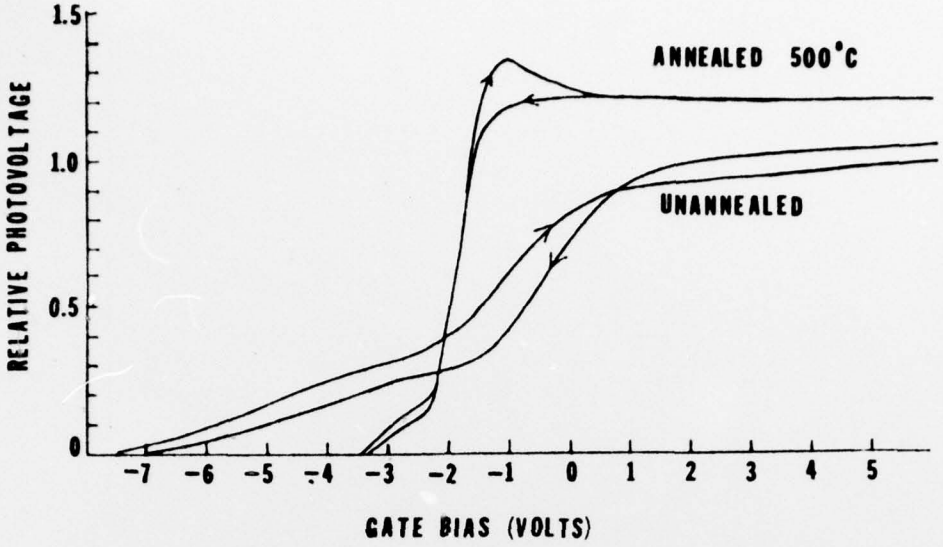

Fig. 5. Real component of photovoltage at 200 Hz for annealed and unannealed photoresist samples.

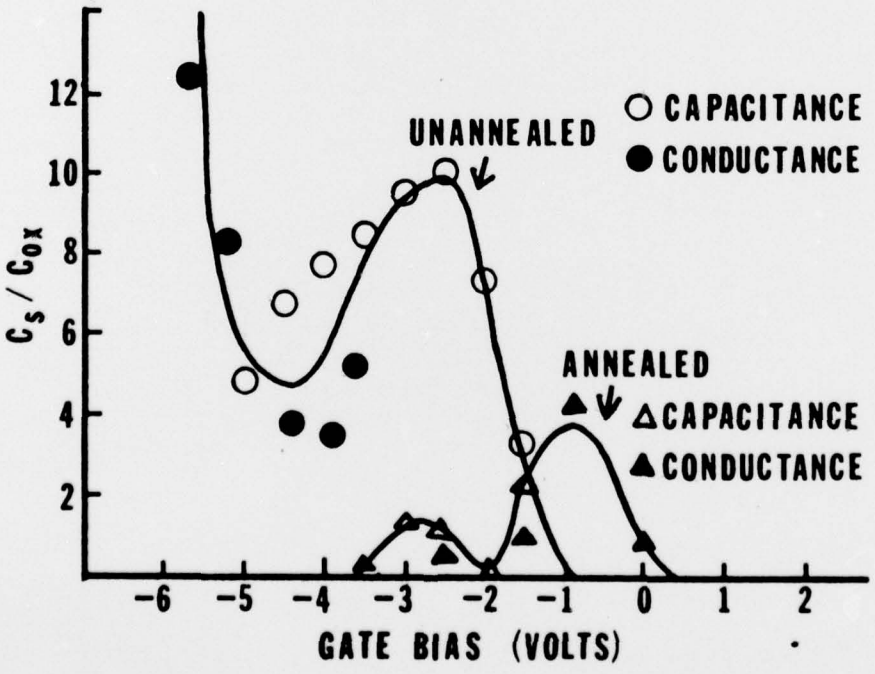

Fig. 6. Plot of C_s/C_{ox} for annealed and unannealed photoresist samples.